Time's Direction and Orthodox Quantum Mechanics: Time Symmetry and Measurement

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Abstract

It has been argued that measurement-induced collapses in Orthodox Quantum Mechanics generates an intrinsic (or built-in) quantum arrow of time. In this paper, I critically assess this proposal. I begin by distinguishing between an intrinsic and non-intrinsic arrow of time. After presenting the proposal of a collapse-based arrow of time in some detail, I argue, first, that any quantum arrow of time in Orthodox Quantum Mechanics is non-intrinsic since it depends on external information about the measurement context, and second, that it cannot be global, but just local. I complement these arguments by assessing some criticisms and considerations about the implementation of time reversal in contexts wherein measurement-induced collapses work. I conclude that the quantum arrow of time delivered by Orthodox Quantum Mechanics is much weaker than usually thought.

Keywords: Arrow of time – Quantum Mechanics – Collapse – Measurement

1. Introduction

Whether non-relativistic quantum mechanics (QM henceforth) exhibits an arrow of time has been to a great extent an interpretation-dependent matter. The problem has, to a great extent, hinged upon which is the dynamics of QM and whether it is time-reversal symmetric or not. On the one hand, it has been widely accepted that, as long as quantum systems evolve unitarily according to a free Schrödinger-type equation, QM is time-reversal symmetric, and thereby, it exhibits no intrinsic (or built-in) arrow of time. On the other, it has been argued that some interpretations of

QM change the dynamics in such a way that QM becomes time-reversal asymmetric, exhibiting an inner directionality of time. Whereas bare QM, Wave-Function Realism, Everett's relative-state and Many-World interpretation would fall into the former view, the so-called collapse theories would definitively fall into the latter. Hence, defenders of an *intrinsic* arrow of time have seen collapse theories as a fertile terrain for upholding a well-grounded quantum arrow of time.

Collapse theories basically consist in introducing a non-linear and stochastic dynamics in the quantum formalism, so that the quantum systems evolve almost always according to some Schrödinger-type equation, but under some circumstances, undergo a "hit" or "jump" that collapses their quantum states (or that "reduces" their wavefunctions) onto an eigenstate of some observable. The introduction of these "jumps" intends to solve the measurement problem, accounting for the classical behavior of macroscopic systems. Though the idea of "reduction" and "stochasticity" pervade any collapse-type theory, specific versions diverge over how collapses are brought about, and under which circumstances they are brought about. The first proponents of a collapse-type theory held that collapses were brought about any time a measurement is performed. These measurement-induced collapses (MIC henceforth) are the content of the "Collapse Postulate", or "Projection Postulate". This view became a sort of orthodoxy in the physicists' community up to our days and is one of the dynamical principles (or axiom) of the Orthodox Quantum Mechanics (OQM) along with the Schrödinger equation. Yet, in the 70s, a new family of collapse theories was born –the Dynamical Reduction Program (DRP). While retaining some of its essential features, it aimed to overcome many of MIC's issues by developing a collapse theory on the basis of a *single* dynamics. The jumps would happen spontaneously, independently of any measurement procedure. Both MIC and DRP introduce a dynamical mechanism that would not only guarantee that measurements will always have an outcome, but also would break the time-reversal symmetry of the theory –quantum systems collapse, but they do not *un*collapse.

This paper will focus on OQM and, particularly, on MIC. Several physicists and philosophers have suggested that MIC lays the groundwork for an *intrinsic* quantum arrow of time –since MIC is an axiom of OQM, and MIC turns out time-reversal asymmetric, OQM's dynamics exhibits a built-in arrow of time. Setting aside the numerous interpretative issues OQM has had to face, the idea is persuasive and has received considerable support in the physicists' community as well as in that of the philosophers. However, it is not yet fully clear what is the scope, and what are the details, of the proposal. Under the assumption that OQM is a tenable interpretation of QM, what sort of quantum arrow of time does MIC yield? How does it come to establish a genuine time-reversal asymmetry, if it really does so?

In this paper, I will assess MIC in relation to its time-asymmetric nature and the resultant arrow of time. I will submit that the sort of time-reversal asymmetry that MIC provides us yields an arrow of time much weaker than usually thought. In particular, I will firstly argue that MIC delivers a type of time-reversal asymmetry that supports a non-intrinsic arrow of time, since it greatly relies on non-dynamical information about the quantum state; secondly that it delivers an arrow of time that cannot be extended to the whole universe (i.e., a local rather than a global arrow). To complement my main thesis, I will assess some arguments around how time reversal is implemented in OQM. All these arguments, I believe, downplay the role of MIC to ground a quantum arrow of time, at least as an inner, fundamental feature of the quantum dynamics.

The structure of the paper is as follows. In Section 2, the theoretical basis of MIC and OQM will be briefly presented. In Section 3, the distinction between an intrinsic and a non-intrinsic arrow of time will be introduced along with the relationships between MIC and a quantum arrow of time according to its main defenders. In Section 4, my main arguments will be laid out. First, I will argue that a MIC-based arrow of time cannot be intrinsic because it strongly relies on having available external information about the measurement context. Second, I will show, based on some remarks by John Bell on OQM in cosmology, that MIC cannot yield a global arrow of time. Finally, I will assess some arguments against a MIC-based arrow of time that focus on the implementation of time reversal. In the last section, some concluding remarks and guidelines for future work.

2. Quantum Evolution and Measurements: OQM

The origin of OQM, and of MIC in particular in the 30s, is a first attempt to overcoming the so-called *measurement problem.* The literature on this is abundant, so I will not get into details here (see Albert 1992, Maudlin 1995, Wallace 2007). In a nutshell, the *measurement problem* can be simply posed as follows: the unitary and linear dynamics of QM (i.e., a Schrödinger-type dynamics) cannot account for experimental outcomes, since it predicts that a superposition of states must remain so independently of any measurement, interaction or observation that might eventually be performed. And yet, we always register a definite state, and never anything like superposition. Therefore, QM's dynamics generates underdetermined predictions. OQM was one of the first attempts to overcome this setback in the development of the new quantum theory –QM was in need of an additional postulate, MIC, that accounted for what was macroscopically observed in experiments.

In essence, MIC prescribes that quantum systems undergo a radically different evolution when measured. Conforming to this, OQM prescribes two-fold dynamics for quantum systems: either they evolve unitarily according to some Schrödinger-type equation when not measured, or they undergo a "jump" or "collapse" triggered by a measurement process (Dirac 1935: 36). John von Neumann (1955[1932]) proposed a model for (ideal) measurements that has become canonical in the field, giving a more refined version of MIC. He postulated that two types of interventions exist: one given by measurements and the other given by the passage of time (von Neumann 1955: 351). Both sorts of interventions (or processes, as he has also called them) are of a different nature: while the first is statistical, the second is causal. In analyzing in detail these two types of processes, von Neumann claims:

> "Why then do we need the special process 1 for the measurement? The reason is this: In the measurement we cannot observe the system **S** by itself, but must instead investigate the system **S+M,** in order to obtain (numerically) its interaction with the measuring apparatus **M**. The theory of the measurement is a statement concerning **S+M**, and should describe how the state of **S** is related to certain properties of the state of **M**". (Ibidem: 352)

Let us see all this in a simple example. Suppose that a Stern-Gerlach device is oriented to measure spin along the *z* axis. According to QM, once the electron is correlated with the *z*-device, we will end up with a state like

$$|\psi\rangle_z = \sqrt{\frac{1}{2}}\left(|\uparrow\rangle_z|"z\ up"\rangle^D + |\downarrow\rangle_z|"z\ down"\rangle^D\right) \tag{1}$$

Eq. 1 means that the quantum state of the composite system (electron plus the *z*-device) is in a superposition of states. This superposition will evolve unitarily and deterministically according to the Schrödinger equation. However, nothing in Nature (or in experiments) seems to exhibit superpositions, but only determined states[1]. So, OQM goes, something else must be added to the

[1] Dieks 2019, however, suggests that superpositions can be detected at the mesoscopic level.

Schrödinger-type dynamics to select one of the terms and break the superposition chain. This is performed by MIC, which asserts that the quantum state in eq. 1 will undergo a completely different sort of evolution when measured, abruptly and suddenly collapsing onto either of its eigenstates, $|\uparrow\rangle_z|"z\,up"\rangle^D$ or $|\downarrow\rangle_z|"z\,down"\rangle^D$. In this way, we obtain an explanation of why we observe what we actually observe after measurements.

It is evident that, according to OQM, measurements play a crucial role in understanding quantum evolutions. After all, quantum-mechanical results and predictions are about quantum systems *and* measurement devices (as von Neumann stresses). So, even though the Schrödinger equation correctly describes the evolution of any quantum state in isolation, this is unimportant (von Neumann 1955: 357) from the quantum mechanics' *complete* viewpoint. MIC, consequently, aims to complete QM by extending the list of dynamical axioms (or postulates) of QM.

3. Measurement-Induced Collapses and the Arrow of Time

In OQM, the question of whether QM exhibits any preference for one direction of time becomes that of whether OQM involves some time asymmetric element (either in its dynamics or elsewhere) that could lay the foundations for an arrow of time. As I mentioned above, it has been argued that OQM indeed provides us with the right sort of elements to capture a quantum arrow of time. This claim has come up in various places (it appears, for instance, in Aharanov's 1964 critical paper as an already widespread belief. See also, for instance, Popper 1982, Penrose 1989, Price 1996, Arntzenius 1997, Lucas 1999, Healey 2002, Atkinson 2006, Ellis 2013, Callender 2018: 94 and references therein). For instance, Frank Arntzenius (1997) has defended that collapse theories introduce an arrow of time since

> "[in the half-silvered mirror case] such theories say that there are invariant forward transition chances for each of the possible initial quantum state to the possible collapsed states after the interaction (…). One cannot add some set of invariant backward transition chances to such theories, while retaining an empirically adequate theory, since the backward transition frequencies in the phenomena are highly non-invariant when one varies the frequencies with which the photons are emitted from the possible sources" (1997: S218)

For David Atkinson, the time asymmetry in OQM (in a more Copenhagen guise) comes actually from 'observations' (Atkinson 2006: 540). In any case, a collapse-induced time asymmetry has been probably popularized within the philosophy of physics field by Roger Penrose (1989) and a very simple thought experiment. This is a good starting point to assess the proposal, but, before getting into it, I will briefly distinguish two senses in which we can speak of an arrow of time –an *intrinsic* and a *non-intrinsic* sense.

3.1. Intrinsic and non-intrinsic arrows of time.

Many arrows of time can be found in Nature –phenomena exhibiting entropy-increasing behaviors, phenomena involving radiation, asymmetric decay processes, among many others. The existence of such arrows is out of any doubt. The philosophical problem, though, is twofold. First, what is the relation among different arrows of time? Second, where do such arrows of time come from? I will draw my attention towards this latter question.

To begin, it is useful to properly qualify the different arrows of time. There seems to be a sense in which an arrow of time can be said to be *intrinsic* to the dynamics of a theory. Paul Horwich (1987), for instance, claims that an intrinsic arrow of time is given by intrinsic properties of a theory's dynamics, which he relates to the property of being time-reversal invariant. The overall idea is that such an arrow of time is *built in* to a theory's dynamics, meaning that the dynamics alone exhibits the asymmetry, without depending on any external property or condition. The argument probably relies on the relation between a theory's dynamics and its underlying space-time geometry –if a theory's dynamics is time-reversal (a)symmetric, it would reveal an intrinsic (a)symmetry in the structure of the space-time posed by the theory (see, for instance, Earman 1989, North 2008). In general, defenders of non-reductionist accounts of the arrow of time have defended that an *intrinsic* arrow of time, if it exists, it will be given by an intrinsic property of the space-time (see Earman 1974, Maudlin 2002), which can come to be known through a violation of time-reversal invariance at the level of the dynamics (Horwich 1987).

To be more precise, suppose a physical theory T, whose models can be portioned in two classes: those with t increasing (W_f) and those with t decreasing (W_b). So, W_f will include all those evolutions going in the forward direction of time, and W_b those going backward. If a theory's dynamics is time-reversal symmetric, then it will produce a pair of time-symmetric twins as models, that is, W_f and W_b. In addition, the time-reversal transformation gives a mapping from solutions of one class to solution of the other. But, if a theory's dynamics turns out asymmetric under time reversal, then its dynamics will only generate either W_f-type models or W_b-type ones.

In consequence, such a map does not exist. So, intrinsic properties of a theory's dynamics (in Horwich's sense) rule out a complete class of possible evolutions. When a theory is non-time-reversal invariant in the aforementioned sense, I submit, it exhibits a built-in or *intrinsic* arrow of time. In particular, we could distinguish between the past-to-future and the future-to-past direction by looking *only* to the sort of structural relations held by observables, derivatives and parameters appearing in the differential equations of motion.

Notwithstanding, there seems to be a different sense in which an arrow of time can be obtained. When we deal with a theory's dynamics that generates both W_f-type and W_b-type models (i.e., it is time-reversal invariant), there is not an intrinsic arrow of time. Yet, it does not entail that there is no arrow of time whatsoever. For instance, a singular model can exhibit an asymmetry with respect to some element in it, despite the fact that the dynamics is time-reversal invariant –the initial conditions of a particular model could be so special that generate an arrow of time *in relation to* such a special initial condition. Such an arrow of time thus depends on some properties of the model, which can be regarded as external to the dynamical equation that generates it. This sense of arrow of time is, in fact, more circumscribed and needs to be imposed through non-dynamical elements. Hence, a non-intrinsic arrow of time, I submit, is one in which we can still distinguish between the past-to-future and the future-to-past direction, but the distinction is not based on a theory's dynamics (which, generally, is time-reversal invariant), but on an external, non-dynamical element.

It is worth noting that the dynamics of interest here is *general* equations of motion belonging to fundamental physical theories. When I say that an arrow of time is intrinsic, or built in to the dynamics, I mean that the general equation of a physical theory (where forces and interactions have been removed) comes out non-time-reversal invariant. This is important because, in general, the introduction of interactions will render the dynamics non-time-reversal invariant –for instance, an inhomogeneous field whose intensity decreases as time goes by; or a classical evolution of a particle rolling over a rough table. In both cases, there seems to be good reasons for taking these asymmetries as coming from the nature of the interactions, and not from an asymmetry *of* time. Time in itself would be shown to be asymmetric *if* the general equations turn out non-time-reversal invariant. I here follow Callender (1995) in claiming that in order to investigate whether physics exhibits an arrow of time in a fundamental sense (that is, as a feature of reality *at bottom*), we should look at *general* equations and their *intrinsic* features (for debate, see Hutchison 1993). In this line, the property of time-reversal invariance will be in fact informative.

3.2. Time asymmetry and Measurements –Penrose's thought experiment

The arrow of time introduced by MIC has been taken to be intrinsic in the sense just mentioned above –only by adding MIC as an axiom to QM, we obtain a full-fledged time asymmetric theory even in their simplest models. If OQM is correct, then a MIC-based arrow of time would exhibit a genuine property of the temporal structure of the (quantum) world. Let us now take a closer look at this idea. Penrose put forward a simple thought experiment to illustrate it.

Penrose starts by recognizing that OQM is a time-symmetric theory if only its unitary part (that is, the Schrödinger equation) is taken into consideration (1989: 354). But, when we pay attention to its *non-unitary part*, given by MIC, the theory turns out to be time *a*symmetric. Imagine the following setup: a lamp *L* at one extreme of an experimental arrangement and a photo-detector *P* at the opposite extreme. Between them, a half-silvered mirror *M*, which is tilted at a 45° angle to the line from *L* to *P*. Suppose now that *L* randomly emits a photon, which is aimed at *P* to be detected. At *L*, a device registers with high reliability the number of photons emitted given a time interval.

When a photon is emitted by *L*, the half-silvered mirror *M* can either reflect it or let it to pass through. Solely considering quantum theory, Penrose says that when a single photon is emitted, the photon's quantum state "impacts" the half-silvered mirror and splits in two parts: one part is reflected with an amplitude of $\sqrt{1/2}$, whereas the other passes through with the same amplitude. Until an observation is eventually made, both parts of the photon's quantum state –Penrose stresses– must be considered as "co-existing" in the forward time direction.

Conforming to the statistical postulate of QM, we know that the probability that the photon reaches the photocell *P* is given by the square of the moduli of the amplitude, $|\sqrt{1/2}|^2 = 1/2$. We could then ask: "Given that *L* registers, what is the probability that *P* registers?" OQM (as well as QM) implies that the probability is exactly 'one-half'. And, after running the experiment many times, we will get (approximately) that probability distribution. We can also infer straightforwardly that *if P* didn't register, then the photon hit the mirror and bounced off toward, say, the laboratory wall.

The thought experiment has, so far, assumed that time was running forward: the photon *was* firstly emitted by *L*, *after* a while reached the half-silvered mirror *M*, and *then* it split in two parts. At the (*future)* end of the experiment, the photon either reached the laboratory wall or was registered by the photocell. For all practical purposes, OQM has predicted the results wonderfully well. But, in order to know whether OQM is time symmetric, we have to consider the situation in the opposite direction of time –whether it generates equivalent results and empirically adequate models.

To find it out, Penrose claims we should rather begin with the following (time-reversed) question: "Given that *P* registers, what is the probability that *L* registers?" Penrose says: "we note that the *correct* experimental answer to this question is not 'one-half' at all, but 'one'" (1989: 358), for if the photocell *P* indeed registers, then it is always certain that the photon was emitted (and thereby registered) by *L*. So, whenever *P* registers it logically follows that *L* also registered the 100% of the time. This is not however what a time-reversed version of OQM retrodicts. It rather retrodicts that if we trace backward in time the photon's quantum state that reached *P*, then it will have one-half of probability of reaching *L*, and one-half of being reflected. In the light of this, Penrose claims that "in the case of our time-reversed question, the quantum-mechanical calculation has given us *completely the wrong answer*" (1989: 358. Italics in the original).

The upshot is that OQM's dynamics gives different results depending on which is the direction of time. What causes this asymmetry is, according to Penrose, MIC: "If we wish to calculate the probability of a past state on the basis of a known future state, we get quite the wrong answers if we try to adopt the standard R [MIC] procedure" (1989: 359). When a measurement takes place at the end of the experimental setup, the superposition collapses onto one of its terms, destroying all information (Penrose's term) about its past. When time reversed, such information cannot be recovered and then we obtain the wrong results. Therefore, it is the MIC-induced asymmetry which indicates that OQM treats the past-to-future direction and the future-to-past direction differently. In other words, the class of models that OQM generates is asymmetric with respect to the class of models that *T*(OQM) –the time-reversed version of OQM– generates. Since it happens that only the models generated by OQM turn out to be empirically adequate, *T*(OQM) must be rejected.

It is clear that the sort of transition between states (from uncollapsed to collapsed state) is what makes a difference. Consequently, the proposal can be generalized. George Ellis (2013), for instance, stresses the time-asymmetric nature of MIC by stating that quantum states may collapse (when measured), but they never "*un*collapse". The process is intrinsically time-asymmetric since any eigenstate $|q_k\rangle$ occurs *after* measuring (i.e., collapsing), that is, *after* the superposition. Furthermore, all coefficients in the superposition we started with have been lost, so the knowledge of the final state says nothing about the initial state. To conclude, in Ellis' words, "the process [MIC] is where the time irreversibility, and hence the arrow of time, is manifested at the quantum level" (2013: 243).

Huw Price (1996) makes the same case in affirming that any measurement process introduces an "objective asymmetry in the structure of reality" (1996: 207) under some assumptions. Within OQM, the state of a quantum system in the period between two measurements reflects the nature of the former instead of the latter. Specifically, if an electron in a superposed state of the observable position is localized by means of a measurement device, then it will unitarily evolve according to the Schrödinger equation and its state will reflect the fact that the electron *was measured* and *localized* by a position-device. If we measure at a later time the electron's momentum with a momentum-device, the electron's state will not reflect the nature of the second measurement (lying in its future) but that of former (lying in its past).

When the situation between two measurements is time-reversed, the result is oddly the contrary. What we would then see, according to Price, is the electron's state evolving toward a state associated with a measurement device in which it is to be involved in the future (1996: 206). OQM, and MIC consequently, typically takes for granted that a quantum system's state depends upon its past state and its past interactions. The fact that things look so weird when running in the backward direction of time would indicate that a deep time-asymmetry lies at the core of MIC.

To sum up, in introducing an additional dynamical postulate, OQM by the same maneuver introduces a time-asymmetric ingredient into quantum theory. Such an asymmetry comes out from the very principles of the theory. So, we could, on firm basis, hold that OQM allows defending an *intrinsic* quantum arrow of time because the theory turns out non-time-reversal invariant. To put it in the vocabulary of Section 2.1, the structure of OQM's solutions is *asymmetric* under time reversal since the set of its empirically adequate models is given either by $W = W^f$ or $W = W^b$, but not both. In W^b we should include evolutions giving us the wrong probability predictions and those quantum systems "uncollapsing" when temporally reversed. These are disregarded by MIC and by empirical results.

4. Arguments against a MIC-based arrow of time

In this section, I will argue that MIC delivers a weaker arrow of time than usually thought. My main thesis will be that it is at best a non-intrinsic arrow of time. If this is so, then it does not rely exclusively on OQM's dynamics, but on some non-dynamical properties. In particular, some epistemic conditions (or external information) related to the measurement context are required in order to obtain the time asymmetry. In consequence, the arrow of time delivered by MIC follows from the MIC mechanism *and* from our epistemic access to the information about the measurement context. In Sub-section 4.2, I will show that a MIC-based arrow of time cannot be global, but only local. That is, it cannot be defined for the whole universe, but uniquely for some regions of it. In Sub-section (4.3), I will assess come concerns around how time reversal should be implemented within OQM. I will discuss a known argument by Callender against Penrose's thought experiment and will claim there that this argument has some problems.

4.1. A non-intrinsic arrow of time

The MIC-based temporal asymmetry seems to solely come out from the MIC mechanism itself – it rules that transitions always go from uncollapsed state to collapsed states. As it stands, however, this is not quite accurate in so much as the theory *also* describes the transition from "collapsed/defined states" to "uncollapsed/undefined states" –for instance, when a quantum system is prepared in a different basis. The above-mentioned transition is true *only if* the quantum state is collapsed in a basis that has been formerly fixed. Yet, we can only come to know that if we previously have information about the measuring device.

Suppose that $|a_1\rangle$, $|a_2\rangle$ are the eigenstates of the observable A, with eigenvalues α_1 and α_2 respectively[2]. Suppose we also design an A-device, which measures the observable A. We know that when the observable A is measured by an A-device, the quantum state will collapse onto either of its eigenstates. However, we also know by QM that it is possible to represent the eigenstates of A in a different basis, say, B with which A does not commute. Hence, we can rewrite each

[2] In what follows, coefficients do not play any special role in the argument.

eigenstate $|a_1\rangle$ as a superposition of B's eigenstates, $|a_1\rangle = \beta_1|b_1\rangle + \beta_2|b_2\rangle$, and the eigenstate $|b_1\rangle$ as $|b_1\rangle = \alpha_1|a_1\rangle + \alpha_2|a_2\rangle$. And the same goes, mutatis mutandis, for $|a_2\rangle$ and $|b_2\rangle$.

The point is that in the "uncollapsed state → collapsed state" transition

$$|\psi_a\rangle = \alpha_1|a_1\rangle + \alpha_2|a_2\rangle \rightarrow |a_2\rangle \quad (2)$$

the state $|\psi_a\rangle$ is also an eigenstate of the observable B in a B-basis, say, $|\psi_a\rangle = |b_1\rangle$. Then, it can be rightfully viewed as the "collapsed state → uncollapsed state" transition

$$|\psi_b\rangle \rightarrow \beta_1|b_1\rangle + \beta_2|b_2\rangle \quad (3)$$

if *any further specification* about the experimental context is given. Now the state $|\psi_b\rangle$ is in an eigenstate of the observable A in a A-basis. Hence, $|\psi_b\rangle = |a_2\rangle = \beta_1|b_1\rangle + \beta_2|b_2\rangle$. The system will then "uncollapse", so to speak, when measured if we represent the state in a different basis. In practice, this is what happens when the initial state in a superposition is prepared (collapsed) in a different non-commuting basis before running the experiment to measure the observable of interest.

However, these ways to fix the bases and to suitably define how the dynamics works require information that cannot be obtained from the dynamics alone. Nothing in the dynamics gives us any hint to establish the right basis to represent the state, and consequently, to define the transition "uncollapsed state → collapsed state". It can be done only in relation to having some knowledge of the experimental setup, which would provide us the information to represent the state in the right basis. Otherwise, any state may be decomposed in infinite arbitrary ways, some of which are compatible with "uncollapsing" scenarios. The observer's epistemic access to the measurement context is what gives the information necessary to represent the state in the right way to distinguish between the "uncollapsed state → collapsed state" transition from the "collapsed state → uncollapsed state" one.

To sum up the point, the right sort of transition to define an atemporal asymmetry does not depend exclusively on intrinsic properties of the dynamics. Nothing in the theory's dynamics tells us how we should represent the state, since it is in principle decomposable in infinite bases, all on equal footing. It is an observer's own interests (the observable she wants to measure) and her knowledge about it which pick the right observable to give the state. Once the observer decides to measure a specific observable, represents the state in the right basis and has the information about the measurement context, it is true that the system will never uncollapse in *that* measurement context and *that* basis, according to OQM. But it should be noticed that the so-obtained asymmetry relies on a conditional whose antecedent involves much more information than MIC.

To be more radical, it is not clear to me that the so-obtained arrow of time is even of any philosophical interest since it seems to greatly depend on observers' interests when measuring an observable and on agreements among them about how $|\psi\rangle$ must be decomposed. Once again, OQM's dynamics remains silent about this, and the required elements come from elsewhere. In consequence, it can be argued that the temporal asymmetry yielded by OQM depends greatly on observers' interests and agreements, which would significantly downplay the intrinsicality (and, I would say, the objectivity too) of any intended arrow of time coming out from OQM.

To reinforce this point, let me make the case in more epistemic terms. Suppose that the information available to us is that a quantum state $|\psi\rangle$ in a superposition of $|a_1\rangle + |a_2\rangle$ was measured by an observer with an unspecified measurement device (it could have been either an *A*-device or a *B*-device). Someone told us that the outcome was an eigenvalue *x*, meaning that the quantum state has collapsed onto some eigenstate. The MIC-based arrow of time proposal will say that a superposition came earlier because it is an uncollapsed state, whereas the yet unknown eigenstate came later, after the measurement, because it is a collapsed state. Nevertheless, if we know *nothing* about the measurement context, whether the measurement device was an *A*-device or a *B*-device, the scenario is entirely compatible with collapsing and uncollapsing scenarios.

If it was an *A*-device, then it is possible to claim that the state collapsed into the eigenstate $|a_2\rangle$. And this in fact displays the right sort of temporal asymmetry we were after. But if it was a *B*-device, then $|\psi\rangle$ can be seen as already in an eigenstate in a *B*-basis, and the measurement does not collapse anything, but just delivered the same eigenstate we put in. And, as previously mentioned, such an eigenstate *is* in a superposition of the observable *A*. The point is that if we *do not know* any of that, we may rewrite the states in a *B*-basis, swapping bases, and then obtain an "uncollapsing" scenario.

Naturally, if we knew we are dealing with a *B*-device, it would be highly confusing to write the state down in a different basis. But this is exactly the point: it all depends on what is the information available to us and this does not come from the OQM's dynamics at all. In an ignorance situation, there would be no matter of fact to assert that what was obtained was either an "uncollapsed state → collapsed state" or a "collapsed state → uncollapsed state" transition. When the information about the measuring device becomes available and everyone agrees on representing the state in the same way, it is relatively easy to decide whether a collapsing or an uncollapsing scenario took place. But, in accepting all this, any attempt to ground an *intrinsic* MIC-based arrow of time rapidly vanishes since it would be relative to the (pragmatic) choice of a measurement device. And it is not obvious at all how this choice could be related to an intrinsic asymmetry of time.

It is probably illuminating to compare with a more promissory candidate for an intrinsic arrow of time –GRW. Any GRW-type theory is essentially a single-dynamics theory that modifies (or "amends") the usual Schrödinger equation by introducing a stochastic term in it. The interpretation attempts to account for the reduction or collapse process by dispensing notions like 'measurement', 'observer' or 'consciousness –collapses take place stochastically and spontaneously. It is clear that GRW's dynamics is non-time-reversal invariant in virtue of the inner elements of its dynamics: no further external information is needed so as to know if a system undergoes an "uncollapsed state → collapsed state" transition. The very dynamics is what yields the asymmetry. It is blatant that the situation is quite different when go back to OQM. It seems to me that GRW-type theories do yield a meaningful *intrinsic* asymmetry, depending exclusively on the dynamics of the theory. A fortiori, this fact can well serve for grounding an *intrinsic* GRW-based arrow of time. If OQM delivers any temporal asymmetry (and any arrow of time) at all, this is so in a different sense, since the dynamics alone, and their intrinsic properties, are not enough.

The defender of an intrinsic MIC-based arrow of time could reply to this argument in the following way. It is a mistake to consider the measurement context as external, for OQM heavily relies on it to get a well-defined dynamics capable of overcoming the measurement problem. She can then argue that the measurement context is already contained in the MIC postulate. Therefore, the temporal asymmetry would be intrinsic to the dynamics, and not extrinsic to it. Yet, I think this strategy won't succeed. One of the main criticisms to OQM is that it hinges heavily upon the notion of measurement, which, rephrasing John Bell's words, cannot appear in the basic vocabulary of a fundamental physical theory –if a measurement is a physical process like any other and OQM intends to be a fundamental theory, then it should tell us what a measurement is and should describe it in quantum mechanical terms. The situation would, however, be the opposite: it rather seems that measurements explain what QM is! (Dickson 2007: 363).

In virtue of this, if the defender of an intrinsic MIC-based arrow of time introduces all the required information about the measurement context as a part of MIC itself, she just overplays even more the role that the measurement context plays not only in the definition of the dynamics, but also in which states are possible. In addition, it would require encoding all observers' experimental interests, since an observer's decision of measuring spin along *z* would already somehow appear in establishing the sort of transition that is dynamically happening. If Bell is right in claiming that a fundamental theory shouldn't so crucially rely on the notion of 'measurement' to detail its principles, then this reply just makes things worse. Therefore, I think this strategy is, at best, far-fetched.

Alternatively, the defender of an intrinsic MIC-based arrow of time might argue that the problem of needing further information about the measurement context is common in the field, resembling, for instance, the so-called preferred basis problem in Everett's interpretation of QM. As already mentioned, the formalism of QM allows for many decompositions of the universal quantum state. In some bases, the quantum state will be in a superposition, whereas in others, it won't. So, the following question arises: why should we choose a decomposition instead of any other? It seems that Everettians cannot give an answer to it without adding some ingredient to avoid an arbitrary choice. Modern Everettians have proposed decoherence as the relevant mechanism that picks a basis in a no arbitrary way, where the macroscopic structures (somehow) *emerge* from coherent states (see Wallace 2010). In a similar maneuver, the defender of an intrinsic MIC-based arrow of time could counter-argue that the measurement basis somehow emerges from the two-fold dynamics *and* an additional mechanism.

However, I think this strategy cannot even get off the ground. If such an additional mechanism really gives us the (emergent) measurement basis, then it not only already solves the measurement problem, but is also more fundamental than MIC. But it seems that this additional mechanism has already done the whole job, making MIC superfluous and eliminable –in the best scenario, any intended intrinsic arrow of time will ultimately follow from the additional mechanism, not from MIC. Therefore, the upheld position has changed, and we are now dealing with a different proposal, no longer based on MIC. In conclusion, I do not see any viable way to introduce the required information in the dynamics to establish the right sort of asymmetric transition without, on the one hand, overplaying the role of measurements in the formulation of a fundamental physical theory or, on the other, downplaying the role of MIC, making it dispensable.

4.2. A local arrow of time

We can go a step further in diminishing the type of arrow of time that OQM delivers. In the previous sub-section, I have argued that MIC yields, at best, a non-intrinsic arrow of time that relies on having information about the measurement context. However, it could be said that such an arrow of time, despite being non-intrinsic, is global, in the sense it can be used to define an arrow of time for the actual universe as a whole. Think of an entropy-based arrow of time depending upon some very special initial conditions. Those who defend the Past Hypothesis hold that such an arrow of time might be not intrinsic (at least in the sense I have introduced in Section 3.1), but it nonetheless serves very well to speak of an arrow of time for the whole universe (see Boltzmann 1877, Albert 2000). Similarly, it could be claimed that, though non-intrinsic, the MIC-based arrow of time is global.

I am afraid that this view is, ultimately, unconvincing. To define a global arrow of time through MIC, we need to start with the quantum state of the universe. If we can define the "uncollapsed state → collapsed state" transition for such a universal quantum state, then MIC can be said to deliver a global arrow of time. Suppose, for the sake of the argument, that we all agree on how the state must be represented. And yet, this won't be enough since in order to define the right sort of transition for a MIC-based arrow of time, the measurement context must be properly described. This description, basically, consists in choosing an observable to be measured and in detailing a measurement apparatus external to the whole universe, which would, hypothetically, make the universal quantum state collapse, and in consequence, define the "uncollapsed state → collapsed state" transition.

However, as John Bell (1981) asked, when the system in question is the whole universe, where is the 'measurer' to be found? (Bell 1981: 611). MIC depends on having an *external* apparatus well-defined, which behaves classically. But if the universal quantum state is really the quantum state of the universe, then the measurement apparatus cannot be any longer external (otherwise, the system at issue wouldn't be actually the *whole* universe). But if this is so, MIC cannot be suitably applied. Therefore, the "uncollapsed state → collapsed state" transition remains undefined and any alleged global arrow of time remains undefined as well.

The problem here, once again, is the strong dependence of OQM on the notion of measurement, which requires the system to be open. This entails that OQM cannot yield anything like a *global* arrow of time through MIC. So, if OQM can conceive anything like a universal quantum state, it is committed to saying that it never collapses but always evolves unitarily according to some universal Schrödinger-type equation. In accepting, as usual, that the Schrödinger equation is time-reversal symmetric, the universe as a whole not only does not exhibit any built-in arrow of time, but it probably does not exhibit any arrow of time whatsoever[3]. If all this is true, then we will end up with a shattered picture of reality: there is a time symmetric universal quantum evolution, on the one hand, and time asymmetric local quantum evolutions wherever a measurement context can be defined. Whereas such a scenario is coherent, it is nevertheless a bit puzzling: how do such time asymmetric local quantum evolutions emerge from a universal time symmetric quantum state? How can the existence of measurement apparatuses be explained on this basis? Even if we can tell a convincing story about how this is possible, the result will remain: OQM would at best deliver a *local* arrow of time.

As last resort, it could be argued that the notion of a *universal* quantum state makes no sense within OQM, since a necessary condition for MIC to be applied crucially depends on having *open* quantum systems[4]. It can hence be said that it is pointless to pressure the view to account for a notion that can by no means be defined within the theory. This can be true, but my point still remains. If we accept that the notion of a universal quantum state is meaningless within OQM, then it just imposes a more radical constraint over the interpretation, ruling out from the very outset any universal quantum state, and with it, any global time asymmetry and any global arrow of time.

4.3 Issues around the time-reversal transformation and MIC

Thus far, the proposal of a MIC-based arrow of time has been assessed focusing on the sort of arrow of time it might generate. In this section, I will change the angle and focus on the implementation of time reversal in contexts wherein MIC works. Craig Callender (2000) and

[3] In the absence of asymmetric boundary conditions.

[4] Many thanks to Carl Hoefer for pointing this out to me.

Steven Savitt (1996) have claimed that the time-reversal operation upon which a MIC-based arrow of time relies has been misconceived. They argue that, under a more adequate time-reversal transformation, OQM comes out time symmetric, and with it, any quantum arrow of time fades away. The conclusion, according to Callender and Savitt, is that the MIC-based arrow of time offers no ground for a quantum arrow of time because the very operation of time-reversal symmetry has been misapplied. I will assess these arguments and contrapose some considerations to show that they don't succeed in providing a workable alternative.

Let me start by noting that Penrose seems to employ extra-quantum mechanical information when judging whether the theory is time symmetric[5]. In particular, in replying to the forward-in-time question "Given that *L* registers, what is the probability that *P* registers?" Penrose appeals to the usual quantum-mechanical expectations. But, in considering the time-reversed question "Given that *P* registers, what is the probability that *L* registers?" Penrose rather appeals to the non-quantum mechanical answer 'one' judged as "the *correct* experimental answer" (Penrose 1989: 358). This does not seem to be fair. Let me explain this in more detail.

To begin, the experiment cannot be *really* carried out in the backward direction of time, so we have to instead imagine what we would expect of an experiment *if* the direction of time were reversed. But, in imagining such a time-reversed scenario, Penrose leaks non-quantum mechanical information when judging what would be the right answer: Instead of saying that *T*(OQM)'s answer would be 'one half' of getting the electron registered at *L*, Penrose says that it would be just 'one', which is not the same to that obtained with OQM. Such a result, Penrose says, is what introduces the asymmetry in OQM for we already know that *L* always registers. Hence, we know that the right experimental value should be 'one' rather than 'one-half'. Therefore, *T*(OQM) generates retrodictions that are not empirically adequate. The upshot is that the theory comes out predictive, but not retrodictive (Callender 2000: 258) This has been also stressed by Satosi Wannabe: "it is precisely irretrodictability that is related to phenomenal one-wayness" (1965: 56)[6]. Hence, MIC inevitably breaks the time-reversal symmetry of the unitary part of the theory since it

[5] Craig Callender (2000) has also raised a similar concern, though he does not develop it.

[6] Even though it's true that in general time asymmetry (or non-time-reversal invariance) and "irretrodictability" may come to be thought as two quite different properties, and one could consequently argue that no temporal directionality should be followed from irretrodictability, it has been argued that in some cases, like non-relativistic quantum mechanics, the implication is right. Earman for instance claims that in any statistical theory non-time-reversal invariance directly follows from irretrodictability. (Earman 1974).

generates results directly in terms of conditional probabilities for states in the future, but not in the past[7].

The question is: where does such a knowledge come from? If we just look at the dynamics and the theoretical content of T(OQM), it is not so clear that we will necessarily arrive at the result 'one'. The answer is that this knowledge comes from having run the experiment in the original direction of time and from extra-quantum mechanical information extracted from how the experiment was settled in the future-headed direction of time. Therefore, this asymmetry seems to be grounded in temporally biased knowledge –empirical information obtained in one of the experimental runs is being (mis)applied to the time-reversed experimental running.

This should already be seen as a red flag. But there is a related, though more general, worry which follows from how time is being inverted in Penrose's thought experiment. When we compare T(OQM) with OQM, we are basically taking the elements and predictions of a physical theory and contrasting them with its time-reversed one. Yet, the notion of time reversal is generally applied to differential dynamical equations, where we have a relatively sharp recipe of how differential dynamical equations should be temporally reversed[8]. But now we are dealing with a much worldlier situation involving photocells and lamps emitting photons. And let me say that we are a bit clueless about what a time-reversed experimental setup would look like.

What Penrose basically does in his thought experiment is to imagine the same objects and the same situation but in the reverse temporal order. Let us call Penrose's time-reversal transformation T^P. So, given the (relevant) sequence where the photon is emitted by the lamp L, hits the half-silvered mirror M, passes through it and reaches the photo-cell P

Future-headed sequence $L \rightarrow M \rightarrow P$

T^P produces the (allegedly) time-reversed sequence

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[7] We could think that by adding retrodictions to the theory the problem vanishes. Richard Healey has showed that this cannot be done without trivializing the theory, if it is statistical. For further details and discussion about it, see Healey (1981: 103-108).

[8] This claim should be tempered though. We have a relatively sharp recipe of how time reversal should be formally implemented *in abstract*, but when it comes to details or concrete instantiations, some problems come up even in such an abstract level. For discussion, see Sachs 1987, Albert 2000, Callender 2000, Roberts 2017, Lopez 2019). For more general discussion on the notion of time-reversal invariance, see for instance Earman 2002, Farr and Reutlinger 2013, Peterson 2015.

Past-headed sequence $T^P(L \rightarrow M \rightarrow P) = P \rightarrow M \rightarrow L$

The question to which the quantum-mechanical algorithm has to respond must be temporally reversed accordingly. By interchanging the terms in the question "Given that L registers, what is the probability that P registers?" turns into the time-reversed question "Given that P registers, what is the probability that L registers?"

It is clear in which sense OQM is time asymmetric *if* MIC and T^P hold. However, it remains to be seen whether T^P is a tenable time-reversal transformation. If it is not, then the time asymmetry in Penrose's thought experiment may be put into question. Indeed, Penrose does not discuss any other alternative, but he just assumes that an inversion of the direction of time amounts to simply reversing the order of the sequence of states and then to working out the corresponding probabilities (assuming extra-quantum mechanical information as was shown before). Yet, there are some other alternatives to consider. For instance, Savitt defines at least three broad notions of time reversal in the literature: (i) *time-reversal$_1$*, which amounts to the mapping $T: t \rightarrow -t$; (ii) *time-reversal$_2$*, which not only maps $t \rightarrow -t$ but also temporally reverses the very *states* (and *objects*) of a sequence; and (iii) *time-reversal$_3$*, which captures the idea that time reversal is motion reversal, and thereby, it must retrace the physical system's trajectory.

Interestingly, Penrose's thought experiment is non-time-reversal invariant only under the first sense of time reversal but is time-reversal invariant in the second and third senses. In the same vein, Callender asks: "why compare $P(S_i \rightarrow S_f)$ with $P\ (S_f \rightarrow S_i)$ and not with $P\ (S_f^T \rightarrow S_i^T)$?" (2000: 256). What Callender finds suspicious is that T^P does not transform the states themselves but leaves them as they were in the original direction of time. He hence claims that is time-reversal invariance$_2$ that amounts to genuinely reversing the direction of time, and not time-reversal invariance$_1$, as Penrose presupposes. Therefore, the genuine time-reversed sequence of Penrose's thought experiment is not given by T^P but by Callender's time-reversal transformation, T^C:

Past-headed sequence $T^C(L \rightarrow M \rightarrow P) = P^T \rightarrow M^T \rightarrow L^T$

where X^T is a time-reversed state or an object in the sequence. Callender gives some hints about how this should be interpreted. He says: "if Penrose is genuinely concerned with TRI [time-reversal invariance], he should treat the *emitter as a receiver* and *vice versa*" (2000: 256. Emphasis added). Therefore, the right time-reversed question to make to the quantum-mechanical algorithm is not "what is the probability that *L* registers, given that *P* registers", but "what is the probability that a *time-reversed L* registers, given that a *time-reversed P* registers".

The problem raised by Callender is that Penrose is misapplying the time-reversal transformation, which leads him to address his own thought experiment from the wrong angle. the *states* (or *objects*) in the sequence as temporally reversed. When we imagine the sequence but also the *states* (or *objects*) in the sequence as temporally reversed, time-reversal symmetry is restored —when we calculate the probabilities generated by $T^C(OQM)$, they are equal to those of OQM (see Callender 2000: 256-257 for an informal proof). Penrose rather imagines that the time-reversed scenario just amounts to reversing the order of the sequence, leaving the states unaltered. There is in fact an asymmetry between $T^P(OQM)$ and OQM, but it is an spurius asymmetry given by a misapplication of the time-reversal transformation.

I am not quite sure, however, that Callender's alternative is any better. It is true that T^P is not the only conceivable time-reversal transformation. Furthermore, it might be not the most adequate implementation of time reversal. Callender and Savitt are right at pointing to this, pushing any defender of Penrose's argument to provide some support for T^P. Nonetheless, I disagree on Callender's conclusion that T^C is rather the right implementation of time reversal. T^C's distinctive feature is that it reverses the states and objects themselves. The problem that I see follow from three possible readings of how this is supposed to be implemented. In one of the readings, the time-reversal transformation radically changes the function of the objects, which entails that the time-reversal transformation *destroys* the objects when time reversed. In the second reading, the time-reversal transformation *swaps* the objects in the series. In the third reading, the time-reversal transformation *reverses* the inner mechanisms of the objects in the series. I will argue that the first reading is unviable, the second leads to triviality, and the third leads to a temporal asymmetry.

Let us start with the first reading. Suppose that T^C is the right way to temporally reverse Penrose's thought experiment. As Callender suggests, it implies that one should treat the emitter as receiver and vice versa. Callender does not add much to this, but I will try to parse it out. T^C at least implies that,

$$T^C(emitter) = receiver \tag{4}$$

It means that a time-reversed photocell should be treated as an emitter. Thus, the time-reversed sequence

$$T^C(L \rightarrow M \rightarrow P) = P^T \rightarrow M^T \rightarrow L^T \tag{5}$$

should be read as saying that a time-reversed photocell emits a photon at t_2 and shortly after the time-reversed photon hits the time-reversed mirror, always with *t* decreasing. Through the quantum-mechanical algorithm, we know that it has one-half chances of passing through the half-silvered mirrored and of reaching the time-reversed lamp, and one-half of being headed to the laboratory wall. As it was mentioned previously, if Penrose's though experiment is so time reversed, then it comes out time-reversal invariant as it delivers the same probabilities for *t* increasing and *t* decreasing.

At this point, it is worth considering the following question: how would a time-reversed photocell work? We know how photocells works in the ordinary direction of time, but we have no clue about how a time-reversed photocell would work. Treating the photocell as an emitter doesn't help so much for a photocell is not the sort of thing that emits anything. Why are we entitled to suppose that a photocell will behave in a completely different way, capable of emitting photons and behaving as an emitter when temporally reversed?

It can be argued that ordinary photocells do not emit anything, but time-reversed photocells do. But this is also bewildering: on which bases should we keep on calling it a photocell? If by time reversing a photocell we obtain something that emits photons, the transformation seems to radically change the way in which photocells typically work. And, once again, on which basis are we allowed to make such an assumption? By time reversing a photocell, we end up with something that does not work like a photocell; it seems, hence, that by T^C-reversing the direction of time the nature of the objects (or states) involved in the sequence is substantially changed, since their functions are radically replaced by their opposites. What puzzles me is that photocells, if we wish to use the word meaningfully, cannot be the sort of thing that emits anything in *either* direction of time, provided that we are still dealing with photocells in some relevant sense. In virtue of this, the time-reversal transformation *destroys* the forward-in-time objects by replacing their functions when time reversed.

Let me pose the problem slightly differently. Photocells may come in various types and with properties, so we can imagine different modal scenarios for photocells. Notwithstanding, if we wish to still refer to photocells meaningfully, a certain sub-group of properties must remain fixed, while some other properties must be necessarily excluded. Otherwise, we would be unable to identify the objects at issue through different scenarios. It seems to me that the property of "functioning like a photocell" (that is, the more general property of "behaving as a receiver") is one of those that must remain fixed. Conversely, the property of "behaving like an emitter" must be excluded. All this in order to identify photocells through different scenarios and to keep talking about photocells meaningfully.

I do not see any reason why this should be different in a time-reversed scenario. A time-reversed photocell in a past-headed experimental running should emit nothing to the same extent that a photocell emits nothing in a future-headed experimental running. Otherwise, we are referring to a different type of object, no longer a photocell. But, in fact, it would be strange that the very functional nature of the objects changes so radically when time is reversed –I see no time-dependent feature in the functional nature of a photocell that required a change if time were reversed. Quite the opposite, if an object's inner nature can freely vary when time reversed, then time-reversal invariance will practically always follow trivially.

And here is where the second reading of the proposal comes over: we should make explicit how a photocell transforms into a different sort of object under time reversal. I think that the only possible choice is to alternatively suppose that

$$T^C(P) = L \tag{6}$$

That is, a time-reversed photocell should be treated *as if* it were a lamp. Analogously,

$$T^C(L) = P \tag{7}$$

Now it seems we are getting somewhere because a lamp is in fact the right sort of thing that can behave like an emitter. This could thus be reworded as following: when an experiment is T^C-

reversed, the time-reversed photocell is capable of emitting because it *is*, in the opposite direction of time, a lamp. This reading, however, leads to a trivial transformation. What is at issue is to test whether time symmetry holds, but if time symmetry can transform the objects (and their state) at will, then it seems that the transformation is designed to leave the experimental setup virtually unaltered. So, both situations are bound to be time-reversal symmetric because the transformation does nothing but a trivial swapping. If a time-reversed photocell is like a lamp, and a time-reversed lamp is like a photocell, we are just swapping names and keeping the same physical situation unaltered.

To put it more drastically: we are simply marking the states and objects with a “^{T}”. And it is blatant that a graphical mark will not produce any physical change! The problem with this implementation is that it implicitly assumes that a change in the direction of time is, so to speak, *innocuous* in the description of any physical situation. It just plays the role of re-parametrizing the time coordinate, of swapping names, and of leaving the experimental setup as unaltered as possible. This is not per se a wrong-headed implementation of time reversal. But I do not see how a substantive philosophical claim may come out from it. After all, we are dealing with a transformation that will surely produce time symmetric scenarios.

Finally, a third reading can be proposed[9]. Time reversal is not about reversing functions, nor about treating objects as if they were different when time reversed. Time reversal is about reversing the inner physical processes that make a photocell and a lamp operate as they do. The mechanisms for how they operate are well understood, so we could reverse the mechanisms and compare them to say clearly whether they are the time-reversed counterpart of the other. It will be enough to consider the operation of the photocell, which is basically an avalanche photodiode which exploits the photo-electric effect. The photocell works via an avalanche effect (impact ionization) at a biased p-n junction of a semi-conductor. A photon is absorbed by an electron in the valence band and excited to the conduction band, which leaves a hole in the valence band. Then, the bias accelerates this electron to a very high energy so that many secondary electrons are produced. This has the effect of creating a current spike, registered as the detection of a photon.

Now let us suppose that (6) holds. Then, the *operation* of time-reversed photocell must be equivalent to the operation of a lamp. However, this is not quite right. In the case of a lamp (e.g.,

[9] Many thanks to an anonymous reviewer for suggesting this additional argument and example.

a LED) the bias injects electrons into the device that recombine with the holes to create photons. But the hole distribution is unusual and must be created when fabricating the LED; otherwise, the device wouldn't work as expected. But, this amounts to implementing special boundary conditions for the process to work. Hence, time reversal is not enough to transform the operation of a photocell into the operation of a lamp (e.g., a LED) –an asymmetric element is introduced into the operation (in the form of a special boundary condition) that renders the process as asymmetric. This reading, in fact, reinforces what has been argued in the previous sub-sections about the non-intrinsic nature of the asymmetry induced via MIC.

To sum up, many of these criticisms are on the right track in pointing that Penrose's time-reversal transformation requires further justification. They are also on the right track in pointing to the fact that there are other candidates that might do a better job. Remarkably, Penrose's time asymmetric experiment may come out time symmetric under a different implementation of time reversal. However, I think we should be a bit cautious here since the other candidates also run into troubles when implemented. So, at this point, I believe the best we can do is to affirm that if the MIC-based temporal asymmetry (Penrose's thought experiment being a particular case) is genuine, it strongly depends upon the sort of time reversal transformation to implement. I do not think that there is a single implementation. To a good extent, I think that the implementation of time reversal hinges crucially upon previously assumed philosophical commitments to be unpacked case by case. In some sense, given the right philosophical framework, any time-reversal transformation might be defendable.

5. Concluding Remarks

In this paper, I have critically analyzed a widely accepted proposal claiming that MIC lays the groundwork for an intrinsic arrow of time in OQM. After introducing the proposal in some detail, I have argued that, at best, OQM delivers a non-intrinsic, local arrow of time. In other words, it delivers, on the one hand, an arrow of time that greatly depends on an agent's epistemic access to information about the measurement context and, on the other, an arrow of time that can be only defined locally, wherever a quantum system may remain open and interact with an external apparatus. These two claims weaken the original proposal. In Sub-section 4.3, I have assessed some arguments against a MIC-based arrow of time that were grounded in the idea that the implementation of time reversal was misconceived. I have argued there that the proposed alternatives are not any better. In conclusion, I think that MIC does generate an arrow of time (pace its critics), but it turns out to be much weaker than originally thought (pace its defenders). In the end, I think it is not of any philosophical interest.

Notwithstanding this, defenders of collapse theories still have some hopes. As it was pointed out in the introduction, MIC is just one of the members of collapse theory families. Despite being almost the orthodoxy within the physicists' community, OQM has lately been rather delegated among philosophers of physics. Much attention has been instead drawn towards different collapse models within the DRP, where collapses produce spontaneously and independently of measurements. It has been argued (see, for instance, Albert 2000 and Esfeld and Sachse 2007) that DRP (and in particular, GRW) does in fact provide the grounds for a genuine intrinsic arrow of time. The analysis of the relationship between DRP and a collapse-based arrow of time is left for future research.

Compliance with Ethical Standards

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References

Aaserud, F. and Heilbron, J. (2013). "Love, literature and the quantum atom (Niels Bohr's 1913 Trilogy Revisitied)". *Isis,* 106 (4): 972-973.

Aharonov, Y., Bergmann, P., and Lebowitz, J. (1964). "Time symmetry in the quantum process of measurement". *Physical Review B,* 134(6): 1410-1416.

Albert, D. (1992). *Quantum mechanics and experience.* Cambridge, MA: Harvard University Press.

Albert, D. Z. (2000). *Time and Chance*. Cambridge, MA: Harvard University Press.

Arntzenius, F. (1997). "Mirrors and the direction of time". *Philosophy of Science*, 64: 213-222.

Atkinson, D. (2006). "Does quantum electrodynamics have an arrow of time?". *Studies in History and Philosophy of Modern Physics*, 37 (3): 528-541.

Bell, J. (1981). "Quantum mechanics for cosmologists", in Isham, Penrose, Sciama (eds), *Quantum Gravity*, Oxford: Oxford University Press, pp. 611-637.

Bohr, N. (1935). "Quantum mechanics and physical reality". *Nature*, 136: 1025-1026.

Boltzmann, L. (1877). "Uber die Beziehung zwischen des zweiten Hauptsatze der mechanischen der Warmetheorie" ("On the Relation of a General Mechanical Theorem to the Second Law of Thermodynamics"), *Sitzungsberichte, K. Akademie der Wissenschaften in Wien*, Math.-Naturwiss, 75, 67-73 (reprinted in Brush 1966).

Brock, S. (2003). *Niels Bohr's Philosophy of Quantum Physics*. Logos Verlag.

Callender, C. (1995). "The metaphysics of time reversal: Hutchison on classical mechanics". *The British Journal for the Philosophy of Science*, 46: 331-340.

Callender, C. (2000). "Is time 'handed' in a quantum world?" *Proceedings of the Aristotelian Society*, 100: 247-269.

Callender, C. (2018). *What makes time special?* Oxford: Oxford University Press.

Cushing, J. (1994). *Quantum Mechanics: Historical Contingency and the Copenhagen Hegemony*, Chicago: University of Chicago Press.

Dieks, D. (2019). "Quantum mechanics and perspectivalism". In Lombardi et al. (eds), *Quantum Worlds: Perspectives on the Ontology of Quantum Mechanics*, Cambridge: Cambridge University Press, pp. 51-70.

Dirac, P. (1935). *Principles of Quantum Mechanics*. Oxford: Oxford University Press.

Earman, J. (1974). "An attempt to add a little direction to 'The Problem of the Direction of Time'", *Philosophy of Science*, 41: 15-47.

Earman, J. (2002). "What time-reversal invariance is and why it matters". *International Studies in the Philosophy of Science*, 16: 245-264.

Ellis, G. F. R. (2013). "The arrow of time and the nature of spacetime", *Studies in History and Philosophy of Modern Physics*, 44: 242-262.

Farr, M. and Reutlinger, A. (2013). "A relic of a bygone age? Causation, time symmetry and the directionality argument". *Erkenntnis*, **78**: 215-235.

Faye, J. (1991). *Niels Bohr, his Heritage and Legacy*. Kluwer: Springer.

Faye, J. (2014). "Copenhagen Interpretation of Quantum Mechanics". In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy*. URL = http://plato.stanford.edu/archives/fall2014/entries/qm-co penhagen/

Healey, R. (1981). "Statistical theories, quantum mechanics and the directedness of time". In Healey, R. (ed.), *Reduction, Time and Reality*, Cambridge: Cambridge University Press, pp. 99-128.

Healey, R. (2002). “Can physics coherently deny the reality of time?”, in Callender, C. (ed.), *Time, Reality and Experience*, Cambridge: Cambridge University Press, pp. 293-316.

Horwich, P. (1987). *Asymmetries in Time*. Cambridge, MA: MIT Press.

Hutchison, K. (1993). “Is classical mechanics really time-reversible and deterministic?” *The British Journal for the Philosophy of Science*, 44: 307-323.

Lopez, C. (2019). “Roads to the past: how to go and *not* to go backward in time in quantum theories”. *European Journal for Philosophy of Science*, 9: 27.

Lucas, J. (1999). “A century of time”. In Butterfield, J (ed.), *The Arguments of Time*, Oxford: Oxford University Press, pp. 1-20.

Maudlin, T. (1995). “Three measurement problems”. *Topoi*, 14: 7-15.

North, J. (2008). “Two views on time reversal”. *Philosophy of Science*, 75: 201-223.

Maudlin, T. (2002). “Remarks on the passing of time”, *Proceedings of the Aristotelian Society*, 102: 237-252.

Penrose, R. (1989). *The Emperor’s New Mind.* New York: Oxford University Press.

Peterson, D. (2015). “Prospect for a new account of time reversal”. *Studies in History and Philosophy of Modern Physics*, 49: 42-56.

Popper, K. (1982). *Quantum Theory and the Schism in Physics*. London: Hutchinson.

Price, H. (1996). *Time´s Arrow and Archimedes’ point: New Directions for the Physics of Time*. New York: Oxford University Press.

Roberts, B. (2017). “Three myths about time reversal invariance”. *Philosophy of Science,* 84, 2: 315-334.

Sachs, R. (1987). *The Physics of Time Reversal*. London: University Chicago Press.

Savitt, S. (1996). “The direction of time”. *The British Journal for the Philosophy of Science*, 47: 347-370.

Von Neumann, J. (1932). *Mathematische Grundlagen dder Quantenmechanik*. Berlin: Springer-Verglag. English version: *Mathematical Foundations of Quantum Mechanics* (1955). Berlin: Princeton University Press.

Wallace, D. (2008). “Quantum Mechanics”, in Rickles (ed), *The Ashgate Companion to the New Philosophy of Physics* (Ashgate, 2008). Published online under the title: "The Measurement Problem: State of Play".

Watanabe, S. (1965). “Conditional Probability in Physics”. *Progress of Theoretical Physics Supplement, Extra Number:* 135-167.

Zeilinger, A. (2005). “The Message of the Quantum.” *Nature*, 438(7069): 743.